



## PYROLYSIS OIL UTILIZATION IN 50KWE GAS TURBINE

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### ABSTRACT

The concept of using pyrolysis oil (PO) derived from biomass via a fast pyrolysis route for power and heat generation encounters problems due to an incompatibility between properties (physical and chemical) of bio-oil and gas turbines designed for fossil fuels. An extensive research has been performed on the production and improvement of pyrolysis oil but only few investigations were carried out on its utilization. The latter have shown a major difference in behavior of pyrolysis oil compared to fossil fuels during combustion processes. In this work, pyrolysis oil is co-fired with diesel in a 50 kWe gas turbine operating in idle mode. Stable mixtures with up to 20 wt.% of pyrolysis oil and diesel fuel were produced with utilization of a surfactant agent. To prevent feeding line deterioration due to acidic character of pyrolysis oil, a stainless steel nozzle was employed. Furthermore, the fuel emulsion was preheated up to maximum temperature of 80 °C in order to reduce the effect of high viscosity on the atomization process. Diesel distillate #2 was used as a reference fuel for a comparison of gas turbine performance and emissions with various PO content in the blends. During the combustion investigations, the amount of pyrolysis oil was gradually increased with simultaneous decrease of preheating temperature. In all investigated cases, the gas turbine was running stable at its maximum rotational speed (RPM). The CO level resulting from the study with different blends was generally slightly higher in relation to the diesel distillate fuel. NO emissions were in the range of few ppm and almost no detectable with common gas analyzing equipment. After a few hours of continuous operation, there were no signs of deterioration or contaminations inside the combustor. The study shows that pyrolysis oil gradually can be introduced in the market of fossil fuels and benefit to green power generation.

### 1 INTRODUCTION

The paper is focused on the utilization of the biomass in gas turbines for electricity and heat production. The investigated biomass is in the form of bio-oil from the fast pyrolysis process. Typically during pyrolysis process, 60 – 75 wt. % of the feedstock is converted into pyrolysis oil [1, 2]. The remaining mass are char and non-condensable gases which can be combusted and reused for pyrolysis process, biomass drying, or heat and power generation. Only few percent of energy in form of heat is lost in the process.

Pyrolysis oil has several major advantages over the conventional biomass and fossil fuels. Since the pyrolysis oil is biomass in liquid form it can be easily transported to a place of destination and burned there for electricity and gas production, or used in small CHP installations built nearby the place where the feedstock for pyrolysis oil is produced. Other advantages of the pyrolysis oil are high energy density (by factor 5 – 6 higher than the feedstock from which it was produced), it does not compete or interfere food chain (second generation of biofuels), the minerals left from the pyrolysis oil burning might be re-used for soil enrichment. Pyrolysis oil is also neutral for the environment with respect to CO<sub>2</sub> emission and it follows the climate policy of EU about the use of renewable sources for energy production in 2020.

All the aforementioned benefits make the pyrolysis oil a new desired source for energy production. However, there are difficulties in direct application of pyrolysis oil in conventional gas turbines. The chemical and physical properties of any pyrolysis or bio-oil differ significantly from those of diesel oils, see Table 1. High viscosity ( $\geq 20$  cSt at 40 °C),

delayed ignition time (CN ~ 14), low heating value (LHV ~ 17 MJ/kg), corrosion effect (pH between 2 and 3), chemical instability (aging) and solid content (< 0.5 wt%) make pyrolysis oil a challenging fuel for utilization [3 – 5]. The impact on gas turbine efficiency and life time, combustion quality, NO<sub>x</sub> and particles emissions are the main issues. Gas turbines have a major advantage over other types of internal combustion engines operating on pyrolysis oil due to the continuous operating cycle which makes them less susceptible for a delayed ignition time. To utilize the enormous potential of pyrolysis oil as a fuel of the future, an additional fundamental work on its combustion behaviour and interaction with gas turbine elements must be done.

	LHV [MJ/kg]	Viscosity @20 °C [cP]	Density [kg/m <sup>3</sup> ]	Surface tension [mN/m]	Flash point [°C]
Pyrolysis oil (fresh)	17.0	>25.0	1150	36	>40
Ethanol	28.9	1.3	790	22	>15
Biodiesel	37.3	6.0	880	32	>130
Diesel #2	41.7	4.0	830	28	>55

**Table 1. Properties of various fuels**

The investigations of the pyrolysis oil or any bio-oil are mostly limited to upgrading oil properties (mainly with respect to viscosity). Only few experiments were done on combustion of these bio-fuels in gas turbines. In one of the first studies on bio-oil application in gas turbines conducted by Moses and Bernstein [6], it was concluded that developing fuel specification for pyrolysis liquids is necessary to assure fuel quality and minimize costs of turbines development. Otherwise, major modifications in gas turbines have to be done to include the effect of physical and chemical properties of bio-oil with respect to atomization, combustion efficiency, gaseous and particulate emissions, soot formation, corrosion and erosion of combustion chamber walls and turbine blades.

In other research, Canadian corporation - Orenda Aerospace built a 2.5 MWe class GT2500 gas turbine suitable for low grade fuels combustion including pyrolysis oil [7]. The turbine was equipped with a tubular combustion chamber which was coated to prevent contaminations and corrosion (due to high alkali content in presence of chlorine). To maintain the same operational power as during tests with diesel oil, the nozzle section was modified to allow fuel heating and to enlarge fuel mass flow rate. These modifications compensated low heating value and high viscosity of the bio-oil. The tests have shown severe atomization problems. The size of the droplets was found to be twice the size of diesel droplets. Also the spray angle was changed. Damage was reported from combustion tests in the first stage of turbine blades, in the liner and nozzles. Emission of NO<sub>x</sub> and SO<sub>2</sub> was depended on the investigated bio-oil however it was smaller with respect to diesel oil #2. NO<sub>x</sub> was reported at level of 60 ppmv and SO<sub>2</sub> at 2 ppmv. For diesel oil the values were 321 and 7 ppmv, respectively. The particulates emissions were higher than those from diesel fuel in all cases.

At the Institute for Energy and Environmental Technology of the University of Rostock a study on the combustion of pyrolysis oil was conducted on a small scale gas turbine producing 75 kWe power [8]. Since it was not possible to operate the engine with pyrolysis oil only, the dual fuel feeding line was implemented. The gas turbine operated on dual mode with 73% of the nominal power. About 40% of the total power was produced from the bio-oil. The use of bio-oil in the turbine resulted in deposits in the combustion chamber and on the turbine blades. This deposit could be removed only by use of mechanical treatment. This was hazardous in respect to a long term operation. The exhaust gases composition presented significant higher CO and HC emission, whereas NO<sub>x</sub> was lower in comparison with diesel fuel.

Several tests were performed on the combustion chamber of a gas turbine only. At the University of Madrid mixtures of pyrolysis oil and ethanol were studied [9]. Tests have shown that the atomizer produced 20° a spray cone angle running on pyrolysis oil, whereas

for diesel fuel, this angle was equal to  $60^\circ$ . The observed emission of CO and NO<sub>x</sub> as well as combustion efficiency were similar to JP4 fuel.

Spray atomization of bio-oil was studied at Zhengzhou University with cooperation with Zheng Zhou HengXing Science and Technology [10]. The resulting bio-oil spray was characterized by fine droplet size and good spread angle. For starting up and closing the system, diesel fuel was used. At air factor equal to 1.5 the NO<sub>x</sub> concentration in exhaust gases was about 350 ppm, CO about 10 ppm and SO<sub>x</sub> around 20 ppm.

The Cranfield University with cooperation with Bioenergy Research Group investigated exhaust gases composition and their corrosion effect on the combustion chamber parts using lab scale test-rig [11]. High-combustion efficiency and relatively low ash deposition rates were found during combustion of pyrolysis oil. The deposit formed on the walls was easy to remove. A low chlorine level in the deposits was measured indicating minor effect on high temperature corrosion.

In the most recent atomization study for viscous fuels performed at the University of Twente with application of particle/droplet image analysis [12] it was concluded that for pyrolysis oil proper atomization with utilization of pressure swirl atomizer, the viscosity must be lowered to 7 cP. Otherwise, the ligaments formed in the nozzle near-field region negatively affects combustion process. The combustion tests at micro gas turbine performed at the same university with various viscous fuels extended this assumption to 9 cP [13, 14]. Elevated viscosity has been found responsible for an increase in CO emissions.

The available literature data showed that combustion of pyrolysis oil is a new field, which needs more fundamental exploration to make future application of the pyrolysis oil in energetic sector possible. Efficiency of the process, atomization, combustion and exhaust gases composition must be investigated to prove that pyrolysis oil utilization for combustion applications is viable.

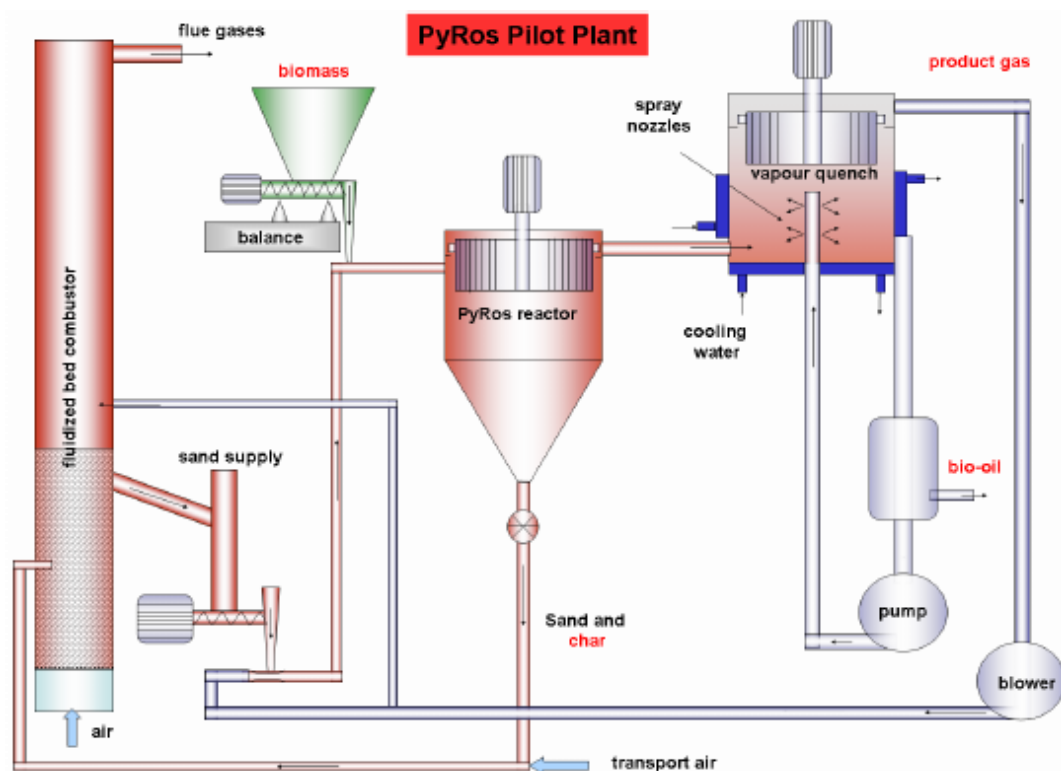
## 2 PYROLYSIS OIL PRODUCTION

The pyrolysis oil used for this investigation was produced at the Laboratory of Thermal Engineering in the pilot plant called PyRos. PyRos operates continuously with reactor temperature in the range of 400 – 650 °C with fully integrated heat addition via a fluidized bed combustor. The capacity of the installation is 10 – 50 kg/h of biomass feed. For hot gas filtration an integrated highly efficient rotational particle separator is used which removes particles in size order of microns. This results in high quality (HHV<sub>dry</sub> of 22.3 MJ/kg) particle free pyrolysis oil. Details information about the PyRos pilot plant can be found in [15]. The schematic overview of the pilot plant is presented in Fig. 1, whereas Table 2 gives average composition of fresh pyrolysis oil produced from a woody biomass. Since the pyrolysis oil used for the gas turbine tests was approx. 8 months old, the measured viscosity was equal to 210 cP at room temperature.

C	H	O	N	Ash	Water
[wt%]	[wt%]	[wt%]	[wt%]	[wt%]	[wt%]
53.9	6.5	38.8	0.8	0.03	23.0

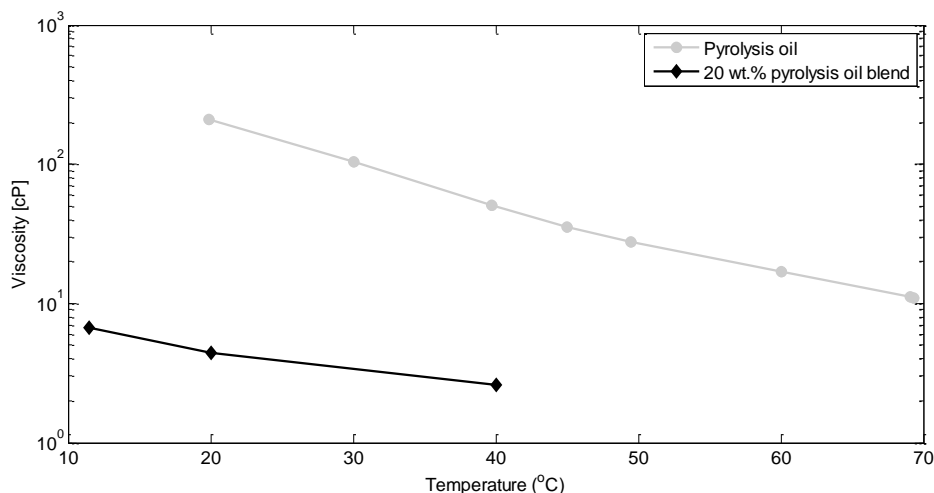
**Table 2. Composition and properties of the produced bio-oil**

From work of Goode [13], Sallevet et al. [12, 14] is known that a certain viscosity is demanded to operate gas turbine equipped with pressure swirl atomizer. It was found that to assure an acceptable atomization level for the combustion process a viscous biofuel should have viscosity below 9 cP. In order to match these properties, the pyrolysis oil produced from woody biomass has been blended with diesel fuel. Because of polar character of the bio oil direct blend with non-polar diesel distillate is not directly possible. Instead a combination of two surfactants which together work as binding agent, is used. The application of various surfactants for such purpose was investigated by several authors, see [16 – 18]. In this work, the surfactants recently used by Martin et al. [19] are selected, mostly due to the minor addition needed for blending diesel fuel with pyrolysis oil to get a stable mixture.



**Figure 1. PyRos pilot plant**

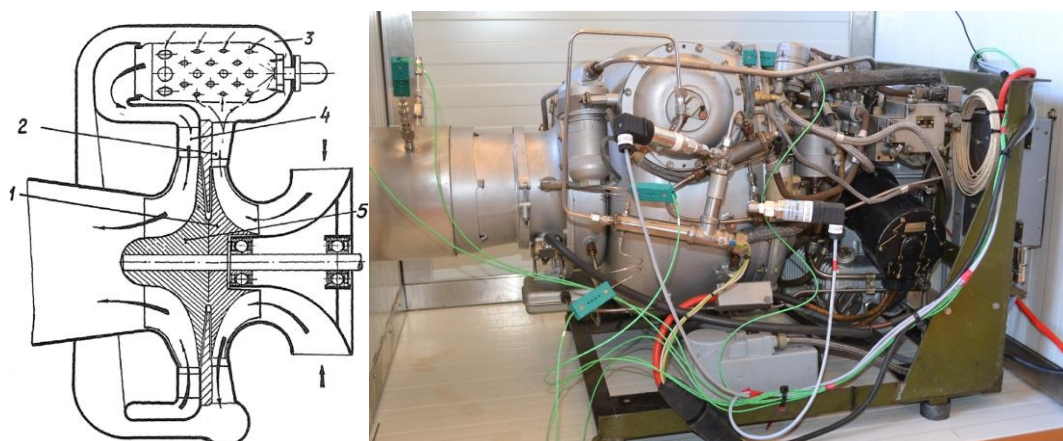
Small sample blends with pyrolysis oil content of 10 wt% and 20 wt% with diesel #2 were prepared. As a binding agent surfactants combination: Zephrym PD2206 (HLB of 4.00) and Atlox 4912 (HLB of 6.00) resulting in hydrophilic-lipophilic balance (HLB) of 4.75. In the work of Martin et al. [19] this HLB value showed the most stable mixtures. After about 1.5 h a separation between fuel components was observed. However, additional stirring allowed the blend to return to its original state. For the experiment two batches of blends were prepared, one of 20 kg 10 wt.% and other of 40 kg 20 wt.% of pyrolysis oil. The viscosity of the 20 wt.% at room temperature was equal to 4.6 cP, whereas the 10 wt.% blend was approximately half of that value. In order to assess an effect of the viscosity on exhaust gas composition, the fuel was preheated from room temperature to 70 °C. The viscosity of the pure pyrolysis oil and the blend as a function of the temperature are presented in Fig. 2.



**Figure 2. Pyrolysis oil and its blend viscosity as a function of temperature**

### 3 PYROLYSIS OIL UTILIZATION

For the combustion research a 50 kWe DG4M-1 radial gas turbine [20] was used equipped with external fuel supply system. The test rig is presented in Fig. 3, whereas its specifications are depicted in Table 3. Except an external fuel supply system, allowing fast switch between various investigated fuels and internal fuel recirculation, only the standard pressure atomizer was exchanged with an AISI 303 stainless steel hollow cone PNR-RXT 0380 nozzle. This was done to avoid corrosion problems in the original equipment. The nozzle with an orifice of 1 mm operating at pressure of approx. 12 bar produces 80 ° spray cone at a fuel flow capacity of 45 l/h. Detailed information about the nozzle can be found in [21]. The turbine is equipped with a gear box and a generator which allow to operate the test rig at different power levels. The produced power is dissipated with application of several heaters. For the current study the least optimal conditions for pyrolysis oil combustion were used, meaning that the gas turbine worked at an idle mode.



**Figure 3. Schematic [20] (left) and actual (right) impression of the 50 kWe gas turbine.**  
On the schematic figure: 1 – compressor, 2 – diffuser, 3 – combustion chamber, 4 – turbine passage, 5 – turbine

Specification	Value
Rotational speed of the shaft	27 600 RPM
Rotational speed after the gear box	6 000 RPM
Nominal power output	51.5 kWe
Pressure ratio	2.6
Air consumption	~1.5 kg/s
Primary air to secondary air ratio	1/3
Fuel (diesel #2) consumption at full load	76 kg/h

**Table 3. Specifications of the gas turbine test rig**

The test rig is equipped with several K-type thermocouples monitoring the temperatures in the fuel line, in the compressor and on the skin of the system. The thermocouples have accuracy of  $\pm 2.2$  °C or  $\pm 0.75$  % of the measured value. For data acquisition the National Instrument NI 9213 is employed.

The pressure measurement inside combustion chamber was done by application of a PMP 1400 with accuracy of  $\pm 0.15$  % of the measurement in the range of 0 – 16 bar. For the pressure in feeding supply system, which is typically much higher and can reach up to 60 bar, the RS TYPE 461 pressure transducer was employed with accuracy of  $\pm 0.25$  % of the measurements in the range of 0 – 100 bar. NI USB-6009 was used for data collection.

The oxygen measurements were performed with Siemens Oxymat 61 which gives an uncertainty of  $\pm 1$  % of the 0 – 25 vol.% range. For CO<sub>2</sub> and CO data, a Maihak Multor 610 with maximum error up to  $\pm 2$  % of the recorded range 0 – 20 vol.% and 0 – 2000 ppm, respectively, were used. As a backup, a portable RBR-ecom KD for O<sub>2</sub>, CO and NO data was

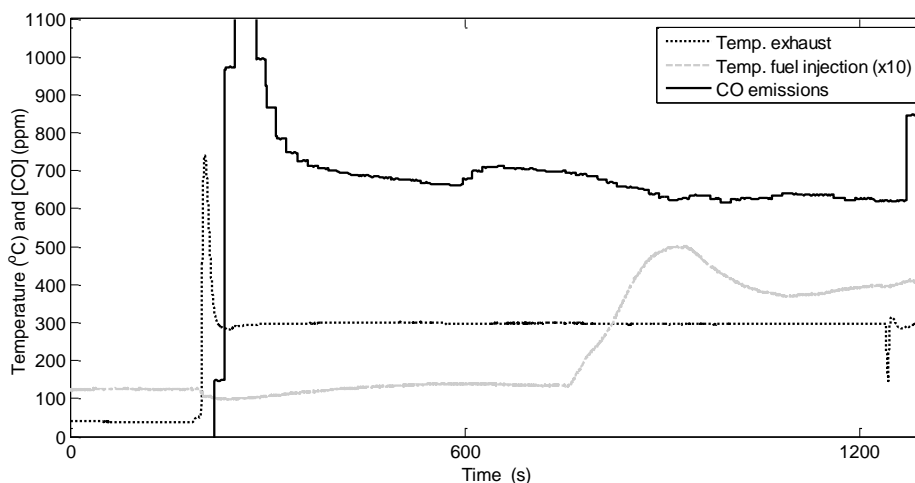


applied. For  $O_2$  range 0 – 21 vol.% the analysers gives an uncertainty of  $\pm 0.3$  vol.% whereas for CO in range 0 – 400 ppm and 400 – 4000 ppm the error is  $\pm 20$  ppm and  $\pm 5$  % of the value, respectively. The NO measurements can be performed in the range of 0 – 2000 ppm with accuracy  $\pm 5$  ppm or  $\pm 5$  % of the measured value.

#### 4 RESULTS AND DISCUSSION

During the 2 hours continuous experiment there were no difficulties in stable operation of gas turbine at maximum RPM conditions. For the pyrolysis oil blends an increase of atomization pressure was necessary to cover the change in the heating value. No smoke or change in the exhaust gas opaque were observed. Data recorded by RBR ecom KD was consistent with continuous results obtained by application of Oxymat 61 and Multor 610, thus for the sake of readability only the later results are reported here. To avoid negative influence of elevated temperature on pyrolysis oil and blend stability, the fuel was preheated not in the fuel tank, but at the location directly in the front of the nozzle. Oxygen level measured in the exhaust gas was constant and equal to 18.8 vol.%.

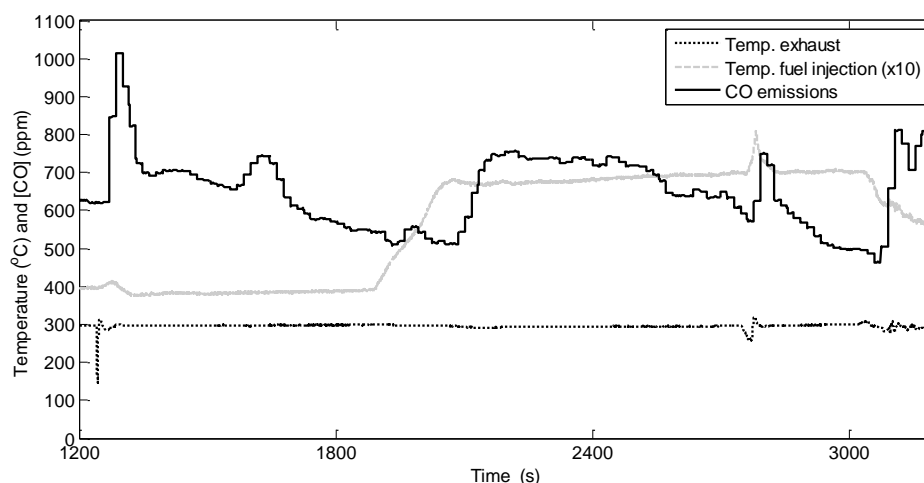
For the start-up of the gas turbine a diesel fuel was used in order to assure a proper preheating of the combustion chamber before pyrolysis oil addition. Also the shut-down of the system was done with diesel fuel to flush the remaining pyrolysis oil and avoid its possible polymerization at the nozzle exit and in the feeding line. As reference case, experiments with diesel distillate at room temperature were performed followed by test conditions with fuel temperature increased till approx. 40 °C. Atomization pressure was constant at level of 12 bar. The experimental data from the diesel fuel study can be seen in Fig. 4. The first 250 s the gas turbine used to obtained a nominal 100 % RPM. Then for about 10 min. the fuel was not preheated and injected to combustion chamber at its ambient temperature 10 °C and viscosity of approx. 5 cP. This resulted in CO emission level of 700 ppm. In the next phase, the diesel distillate was preheated to 40 °C (with peak temperature overshooting at 50 °C). Decrease in the viscosity to 2.5 cP due to fuel preheating had almost immediate reflection in reduction of the CO level to 620 ppm in exhaust gas. After normalization of the results to 15 vol.%  $O_2$  and comparison with data of Gudde [13] and Sallevelt [14] it could be noted that the current carbon monoxide emissions are higher than in the aforementioned works. Since, the temperature of combustion chamber walls, skin of the turbine and exhaust gases were stable, the increased CO emissions could not be related to the transient effects and insufficient warming up of the system. The difference originates from the application in the current tests of different atomizer with reduced atomization cone angle and flow number compared to the other studies. This influenced the droplet size and mixing process inside the combustion chamber resulting in elevated CO emissions.



**Figure 4. CO and temperature of the diesel injection over time for the diesel test case**

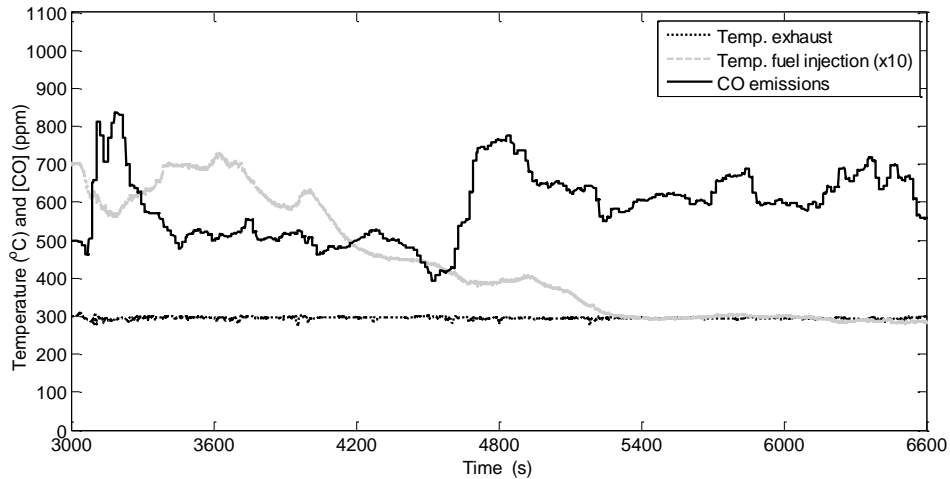
Immediately after the reference measurements with diesel fuel, the flow was switched to the tank containing 10 wt.% of pyrolysis oil and 90 wt.% of diesel. For better miscibility between

the blend components the fuel was constantly recirculated in the tank via a closed feeding loop system. The preheating temperature was kept at 40 °C. The moment of switching fuels is visible as a peak in the CO emissions and sudden drop in exhaust gas temperature around 1 300 s, as reported in Fig. 5. For about 10 min. the gas turbine has operated at this conditions, showing a reduction of the CO from approx. 700 ppm till 520 ppm. After that, the fuel preheating temperature was increased up to 70 °C presenting, however an increase in the CO emissions till level of 750 ppm followed by decrease in the last stage of this experiment to 500 ppm. The atomization pressure during the test was almost constant at level of 15 bar, see also Fig. 7, therefore the increase in carbon monoxide emissions cannot be related to worse performance of the atomizer due to pressure drop. A possible explanation is polymerization process of the pyrolysis oil which could start at 70 °C rising the viscosity of the fuel. The reason for a decrease in CO emissions at the last stage of this test run is not known. An hypothesis could be made that despite of internal fuel premixing by the closed feeding loop system, the heavy fractions of the pyrolysis oil were combusted in the first stage of the experiment, supporting conclusion about polymerization, whereas in the last part, only the light fractions blended with diesel fuel were combusted. This resulted in lack of polymerization and significant decrease of the fuel viscosity. More investigation about this subject is needed.

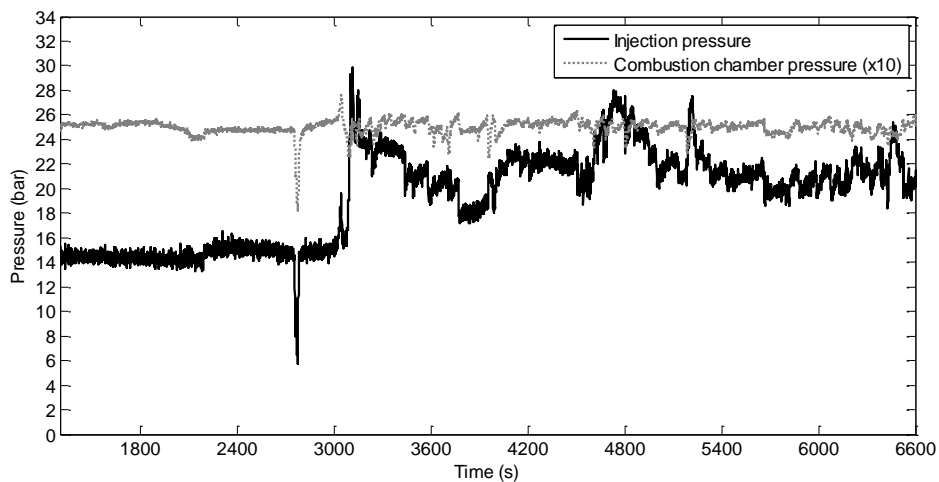


**Figure 5. CO and temperature vs time for 10 wt.% pyrolysis oil blend**

At 3 200 s a 20 wt.% pyrolysis oil blend was poured into the tank (see peak in CO emissions in Fig. 6). Afterwards, for preheating temperature of 70 °C (viscosity about 2 cP) a constant CO at level of approx. 500 ppm were observed. Despite a reduction of the preheating temperature till 50 °C no further increase in carbon monoxide emissions was detected. The fuel polymerization effect observed during the experiment with 10 wt.% pyrolysis oil blend was diminished due to significantly higher atomization pressure and shorter residence time of the fuel in the feeding line. At preheating temperature of 45 °C the minimum of 400 ppm in CO emissions was recorded. Such low values were possible to obtained due to major increase in atomization pressure (thus improved atomization process) which was about twice higher comparing to the experiment with diesel fuel. At about 4 500 s, the tank was refilled with a second batch of 20 wt.% pyrolysis oil blend. Again a rise in carbon monoxide emissions can be observed at that moment followed by stabilization of the emissions at 600 – 700 ppm and 30 °C fuel preheating temperature. During the experiment with 20 wt.% pyrolysis oil the gas turbines experienced substantial fluctuations in the atomization pressure ranging from 30 – 18 bar (see Fig. 7) which suggests that mixing between blend components was not perfect. In the first phase after refuelling the heavy fractions of the blend affected negatively the emissions, whereas in the final phase, the light fractions benefited in decrease of CO content in flue gas.



**Figure 6. CO and temperature vs time for 20 wt.% pyrolysis oil blend**



**Figure 7. Pressure data vs time for 10 and 20 wt.% pyrolysis oil blend**

Despite the fluctuations in CO emissions caused by incomplete premixing of the fuels, it should be noted that during 2 hours experiment with pyrolysis oil blend there were no major difficulties reaching the maximum RPM. The turbine has operated stable and no smoke nor change in exhaust gas opaque was observed. Using fresh pyrolysis oil with lower viscosity should result in an improved performance and lower emissions comparing to the current test. The same is true for the experiments with load conditions instead of the idle operational mode. For all investigated cases, the NO was in range of 2 – 4 ppm. No deposition in the combustion chamber nor in the atomizer was found after the combustion tests, proving that atomization of the fuel was sufficient to combust droplets completely and spray did not reach liner of the system, see Fig. 8.





**Figure 8. Combustion chamber before (left) and after (right) the test campaign**

## 5 CONCLUSIONS

The combustion tests with application of various blends of pyrolysis oil with diesel fuel #2 were investigated in 50 kW gas turbine. The maximum content of the pyrolysis oil in the blend was 20 wt.%. As a binding agent, combination of surfactants Zephrym PD2206 and Atlox 4912 was used. The experiment was performed for approximately 2 hours at various fuel preheating conditions. The gas turbine was operating stable at maximum RPM. The increase in the fuel preheating temperature and injection pressure supported reduction of CO emissions. However, at several stages of the experiment, after pouring the blend into the tank, the influence of limited mixing between polar and non-polar components of the blends was visible in form of sudden CO peaks.

This research proved that pyrolysis oil can be successfully applied in gas turbine system with its minor modification. It can be also concluded that higher wt.% of pyrolysis oil in blend then presented in the current study should be acceptable. Further studies are necessary to harvest the full potential of the pyrolysis oil.

## ACKNOWLEDGMENTS

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